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Development of thermometers for high-speed aircraft

by

D. D. Clark
(Meteorological Office)

AIR MINISTRY
METEOROLOGICAL RESEARCH COMMITTEE

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Summary. The principles of thermometer design are reviewed. Three models were made and tested in a wind tunnel; the results are given in tables and graphs. The model having the best performance (a conical type) was developed further into a production prototype. The lag and radiation errors are calculated and the extension of the use of the thermometer to supersonic flight is discussed.

General principles. A thermometer mounted on an aircraft to measure air temperature does not indicate true air temperature but a temperature higher than true air temperature by an amount which in the ideal case depends only on the square of the air speed. This relationship can be expressed as

$$T_1 - T_o = \frac{\lambda}{2C_p} U^2$$

where T_o is the true air temperature, T_1 the thermometer temperature, U the air speed in cm.sec.$^{-1}$ and C_p the specific heat of air at constant pressure. λ is referred to by most authors as the 'recovery factor' since it can be expressed as the proportion of temperature rise to total temperature rise of completely arrested air, i.e.,

$$\lambda = \frac{T_1 - T_o}{T_2 - T_o}$$

where T_2 is the temperature of air arrested adiabatically. The 'recovery factor' should not be confused with the 'speed-correction coefficient' which is usually expressed in the form

$$T_1 - T_o = \alpha\left(\frac{V}{100}\right)^2$$

where α is the speed-correction coefficient and V is the air speed in knots. Whereas λ depends solely on the characteristics of the thermometer, α depends also on C_p. Since C_p does not vary much, very nearly $\lambda = \frac{3}{4}\alpha$.

It is assumed that λ remains constant; then for air speeds up to about 200 m.p.h. the errors which would arise from small variations in λ are not important. However at high speeds, say 500 m.p.h., an error of 0.1 in λ would give rise to an error in temperature of about 3 degrees Celsius. The effects of variations in λ can be mitigated to some extent by calibrating the thermometer for different heights and Mach numbers; nevertheless it is much better to try to eliminate the variations in λ.

The causes of variations in λ have been dealt with by the present writer (Clark, 1951). An attempt will now be made to describe the development

work arising out of these two reports to produce a thermometer with a constant recovery factor.

Choice of design. There are in effect two possible forms that the thermometer can take. Either it can arrest the air completely, causing an adiabatic temperature rise corresponding to the resulting compressional heating, or else it can interfere with the air stream as little as possible so that the air speed past the thermometer is unchanged and the temperature rise depends on the thermal dissipative and conductive processes taking place within the boundary layer on the surface.

The first variety has been studied very thoroughly by several authors, of whom it is sufficient to mention E. Brun and Max Plan (1949) and L. Malmquist (1948). Although the total-head thermometer, as this type is sometimes called, has generally been favoured for laboratory and wind-tunnel work, nevertheless for meteorological purposes it has certain disadvantages.

In construction the total-head thermometer consists of a hollow chamber open at the forward end and with leak vents at the rear to maintain a slight air movement inside. The temperature of the arrested air is measured by a rapid response element such as a bare resistance wire or thermocouple junction. It is difficult to make a design of this nature robust without sacrificing speed of response and it is essential that response be rapid owing to the low ventilation rate within the chamber. As has been shown also by Malmquist (1948) the recovery factor of these thermometers suffers significant changes with Mach numbers attributed to the nature of the flow inside the chamber. The recovery factor, which is always slightly less than it would be if the air were completely arrested, is dependent on the rate of ventilation which bears a non-linear relationship to the free air speed. This thermometer is also vulnerable to ice formation and once iced up takes some time to clear unless heaters are fitted for de-icing. Although the total-head thermometer appears at first sight to have the advantage of representing a fundamental approach to the problem of temperature measurement in a moving air stream, in as far as it is dependent only on the total energy of the air and not on local stream velocity, nevertheless the constructional compromises required in the engineering of this thermometer make it inferior to a well designed thermometer of the second type, usually referred to as the flat-plate thermometer.

One advantage possessed by the flat-plate thermometer is the high rate of heat exchange existing at the surface when following temperature change which enables a more robust construction to be employed.

For these reasons it was decided to develop the flat-plate type of thermometer for use at high speeds.

Characteristics of flat-plates. A flat-plate thermometer, designed originally by Brewer (1947), has been in regular use aboard meteorological reconnaissance and research aircraft for many years and gives reliable readings to the nearest half degree Celsius at air speeds up to about 300 m.p.h. It consists essentially of a $\frac{1}{2}$ in. metal tube flattened to $\frac{1}{8}$ in. thick and containing a platinum resistance wire element insulated by mica strips. At the sides and underneath there is a radiation shield made of thin metal sheet, all of which offers small resistance to forward motion. Shellard (1949) however has shown that the speed-correction coefficient of this thermometer is less when measured at high altitudes than at low altitudes. The present author (1951) put forward a theory to explain this variation of speed-correction coefficient based on the well-substantiated phenomenon of separation of the boundary layer at the line of adverse pressure gradient behind the leading edge on narrow section aerofoil shapes, which, it was suggested, took place at the high Reynolds numbers associated with low level flying, but not at the lower Reynolds numbers of high level flight. This theory seemed reasonable as the observed variation in speed-correction coefficient agreed with that to be expected, assuming turbulent or laminar boundary layer flow, and, in confirmation, photographs were obtained of separation of the boundary layer taking place on the flat-plate thermometer during wind-tunnel tests carried out at the National Physical Laboratory.

As a further test an experimental flate-plate thermometer was made up with suction slots cut into the surface behind and parallel with the leading edge to keep the boundary layer on the surface and prevent separation. Suction was provided by connecting the duct from the slots to a Venturi tube. This thermometer was flown on one of the Meteorological Research Flight's aircraft; the speed-correction coefficients for the Fahrenheit scale, measured at two altitudes, are given in Table 1. For comparison the speed-correction coefficients for a standard flat-plate thermometer are given as well.

Table 1. Speed-correction coefficient of flat-plate with suction slots

	Height ft.	S.C.C.	Standard deviation	No. of runs
Flat-plate with suction slots	5,500 21,000	1.59 1.60	.10 .03	14 15
Standard flat-plate (for comparison)	5,500 21,000	1.66 1.62	.07 .06	14 15

The variation of S.C.C. is small in the case of the slotted flat-plate compared with the standard flat-plate over the same height range.

In view of the strong evidence that boundary layer changes can cause variations in S.C.C. in flat-plate thermometers, care must be taken in the development of this type of thermometer to maintain constancy in the boundary layer state through careful attention to aerodynamic design.

Temperature gradients. When a thermometer is in thermal equilibrium with the air stream the condition that there be no heat exchange taking place between the air and the thermometer surface (neglecting small losses) is that there be no temperature gradients anywhere on the thermometer surface, because if temperature gradients are present then heat will be conducted from the warmer parts to the cooler parts of the thermometer, requiring heat to be taken up from the air at the warmer parts to compensate this loss and to be given out to the air at the cooler parts warmed by conduction. Since the rate of heat exchange, which is proportional to $k/\nu^{\frac{1}{2}}$, where k is the thermal conductivity and ν the kinematic viscosity of the air, is less at high altitudes than it is at low altitudes, the temperature gradients will also change with altitude becoming less pronounced the higher up we go. Since mean temperature depends on the surface distribution of temperature it also must follow variations in surface temperature gradients. The result therefore of the presence of temperature gradients on the thermometer is an apparent variation in speed-correction coefficient with altitude which, however, only becomes noticeable when these gradients are well-marked. Care must therefore be taken to avoid designs which give rise to pronounced temperature gradients and to reduce the effects of such temperature gradients as exist to a minimum.

Speed of response. Because the lag coefficient of a thermometer is inversely proportional to the square root of the air speed, in order to maintain the same degree of accuracy in reading at high speeds as at low speeds, the thermometer for use at high speeds must be faster in response than that for low speeds in the ratio of the square roots of the air speeds.

In the atmosphere there can exist temperature changes in the horizontal of about 2°C every 5 miles or so and occasionally extreme variations of 4°C can occur in only one mile. If a thermometer is being designed to read to within $\frac{1}{2}$°C of true indicated temperature in an atmosphere having a variation of as much as 4°C in one mile then, at 200 m.p.h., the lag coefficient would have to be less than 2.25 sec. and, at 500 m.p.h., less than 1 sec. The thermometer with a lag coefficient of 2.25 sec. at 200 m.p.h., however, would have it reduced to 1.4 sec. at 500 m.p.h. and would therefore be too sluggish at that

/speed.

speed. The lag coefficient of 1 sec. at 500 m.p.h. on the other hand becomes 1.58 sec. at 200 m.p.h. and that thermometer would be acceptable.

Besides the variation with air speed the lag coefficient varies approximately inversely with the square root of the air density, therefore the lag coefficient of 1 sec. at 500 m.p.h. at low altitudes becomes 2.75 sec. at 500 m.p.h. at 100 mb.

In the design which was finally adopted a compromise between robustness and speed of response gave a lag coefficient of about 2 sec. at low levels at 200 m.p.h. or 1.3 sec. at 500 m.p.h. which becomes 5.5 sec. at 100 mb. at 200 m.p.h. and 3.5 sec. at 100 mb. at 500 m.p.h. These lag coefficients correspond to the temperature errors, given in Table 2, calculated for temperature gradients in the line of flight of 4°C in one mile and also of 0.4°C in one mile at pressure levels of 900 mb. and 100 mb. and for air speeds of 200 and 500 m.p.h., using the formula from the Meteorological Air Observers Handbook (1945), Appendix 3, namely

$$\Delta T = U\, g\, L$$

where ΔT is the lag error, U is the air speed, g the temperature gradient and L the lag coefficient.

Table 2. Temperature errors depending on thermometer lag for lag coefficient of 2 sec. at 900 mb. at 200 m.p.h. calculated for temperature gradients in line of flight of 4°C per mi. and 0.4°C per mi.

Speed m.p.h.	Pressure level mb.			
	900		100	
	Temperature gradient		Temperature gradient	
	4°C/mi.	0.4°C/mi.	4°C/mi.	0.4°C/mi.
200	.44	.04	1.22	.12
500	.69	.07	1.93	.19

Experimental models. Summarizing all these points the problem was to design a flat-plate thermometer with the following characteristics:-

(a) The boundary layer of the air flow over the thermometer must be discouraged from separating from the surface and must be encouraged to stay laminar, i.e., there must not be a negative pressure gradient but preferably there should be a slight positive pressure gradient.

(b) There should be no temperature gradients or, if that is impossible because of (a), their effects should be kept to a minimum.

(c) The speed of response to temperature changes must be rapid.

(d) It must be robust and simple in construction.

Starting from the flat-plate there were two lines of development: one was to concentrate on making the flat-plate as thin and small as possible, the other was to incline the working faces to the air stream to provide the necessary positive pressure gradient. Both these lines were followed up but only the second was continued to completion.

A very slender and miniaturized flat-plate was made, .038 in. thick, $\frac{1}{4}$ in. across and $1\frac{3}{8}$ in. long containing a platinum wire wound on mica but insulated

from the outside case by anodized aluminium strips. The series of tests on this thermometer was not completed as the radiation shield collapsed during a run at M = 0.6. Since the miniature flat-plate design presented no advantage over the conical design no further work was done on it.

The other line of development, requiring an inclined working face, meant either a wedge shape or a cone. As a cone is easier to make it was decided to develop a conical shaped thermometer. A cone of 20° angle was chosen as providing a convenient size and the velocity component on the surface was calculated and plotted to provide an indication of the temperature gradient. See Fig. 7 and Laitone (1947). Details of these calculations are not given here but it suffices to say that the temperature gradient on the surface was found to be least about one third the length of the cone from the tip. To reduce the effects of the gradient, therefore, the temperature sensitive part of the surface had to occupy as small an area as possible in this region. Two conical models were made; one had the temperature sensitive part of the surface restricted to a band of $\frac{1}{4}$ in. depth situated one third the cone's length from the tip, the other had an all metal nose extending up to one third the length of the cone from the tip, the temperature element being inside the metal nose. Photographs of these two models are shown in Fig. 1.

Wind-tunnel tests. All three models were tested in the 8 x 18 in. wind tunnel of the Aerodynamics Division of the National Physical Laboratory.

The recovery factor λ is defined in the equation

$$T_1 - T_o = \lambda \frac{U_o^2}{2C_p} \qquad \text{(1)}$$

$$= \frac{\gamma-1}{2} \lambda T_o M^2$$

where $o < \lambda < 1$, T_1 is the thermometer temperature, T_o is the air temperature, U_o the air speed in cm./sec., C_p the specific heat of air at constant pressure, $\gamma = C_p/C_v = 1.4$ and M is Mach number, also $T_2 - T_o = \frac{\gamma-1}{2} T_o M^2$ where T_2 is the total temperature corresponding to the temperature of completely arrested air assuming adiabatic compression.

Hence $$T_2 - T_1 = (1-\lambda) \frac{\gamma-1}{2} M^2 T_o$$

$$= \frac{(1-\lambda) \frac{\gamma-1}{2} M^2 T_2}{1 + \frac{\gamma-1}{2} M^2}$$

Therefore $$1-\lambda = \frac{T_2 - T_1}{T_2} \frac{\left(1 + \frac{\gamma-1}{2} M^2\right)}{\frac{\gamma-1}{2} M^2} \qquad \text{(2)}$$

Equation 2 expresses λ in terms that can be measured in the wind tunnel. T_2 is the temperature in the intake chamber which was measured by a bare-wire thermometer, T_1 is the temperature, measured by the thermometer model, in the working section and M is the Mach number measured on the tunnel Mach number gauge and corrected for tunnel interference effects.

/During

During each run the total-head temperature drift was never more than about one degree Celsius and the air in the intake chamber was sufficiently near stagnation for no correction to T_2 for air movement to be necessary even at the highest Mach numbers.

The values of λ for each Mach number for the two conical-head thermometer models calculated using formula 2 are given in Table 3 and are shown plotted in Figs. 3 and 4. The corresponding Reynolds numbers are also given in Table 3 and the variation with Reynolds number is illustrated in Figs. 5 and 6.

The total calibration and reading error in T_1 was found to lie within $\pm.043°C$ and that of T_2 within $\pm.015°C$, whence values of the standard deviation of λ were calculated by the method used earlier by the author. These are given in Table 3, column 11, and apply to both models. From Table 3 it is seen that the values of λ for each Mach number show a slight variation. The importance of this variation has been assessed by calculating the errors in true air temperature which would arise if a constant value were assumed for λ throughout. For this calculation the constant value of λ chosen was the mean λ for M = .4 to M = .9, namely .881 for Model I and .877 for Model II and the true air temperature was assumed to be 281°A. The formula for the temperature error is

$$\delta T_o = \delta\lambda . T_o \frac{(\gamma-1)}{2} M^2$$

The results are given in columns 6 and 10 of Table 3.

Table 3. Wind tunnel results. Values of recovery factor

1	2	3	4	5	6	7	8	9	10	11
		Model I				Model II				I and II
Mach No.	Re.10^{-5}	λ	No. of readings	$\sigma_1(\lambda)$	δT °C	λ	No. of readings	$\sigma_1(\lambda)$	δT	$\sigma_2(\lambda)$
.2	.46	.844	18	.012	.08	.717	22	.035	.37	.016
.3	.67	.866	15	.004	.08	-	-	-	-	.007
.4	.87	.875	16	.002	.05	.859	13	.005	.16	.004
.5	1.05	.880	14	.000	.01	.873	13	.002	.06	.003
.6	1.20	.882	11	.001	.02	.877	14	.001	0	.002
.7	1.32	.882	13	.000	.03	.873	14	.001	.11	.001
.8	1.43	.880	18	.001	.04	.876	9	.000	.04	.001
.9	1.50	.886	15	.002	.23	.884	10	.001	.32	.001

$\sigma_1(\lambda)$ = standard deviation of λ

$\sigma_2(\lambda)$ = standard deviation calculated from limits of accuracy of T_1 and T_2

Re = Reynolds number

δT = error in true air temperature which would arise from taking λ = .881 for Model I and λ = .877 for Model II.

The error for Model I is negligible for M = .2 to .8 and is still small at M = .9. There is justification therefore in assigning a constant recovery factor of .881 to the Model I thermometer.

Production prototype. Of the two thermometers, Model I has the better performance and therefore was chosen for development as a prototype. In its final form this thermometer has been reduced to four separate parts shown in Fig. 2.

/The

The body of the thermometer consisting of part of the conical surface and a parallel-walled section with a turned down length for mounting is made of a synthetic resin bonded paper (Tufnol). The sensitive element is made up of a platinum resistance wire of 50 SWG wound on to a thin-walled former made of super-pure aluminium base alloy anodized for electrical insulation, on which had been cut a thread of 200 threads per inch. The problem of providing leads and anchoring points for the platinum wire without adding appreciably to the thermal capacity of the element was solved by clamping copper foil strips to the inside of the former by turning down the ends of the foil into end recesses on the face of the former. These copper foil strips then provided anchoring points for both platinum wire and leads.

The thermometer head when assembled is held in a brass adapter piece which enables it to be mounted in a steel tube sting of 1 in. outside diameter, 17 gauge (see Fig. 2). On a later model the tip, which in Figs. 1 and 2 is shown in synthetic bonded paper, was made in one piece with the threaded rod of K-Monel D and was insulated from the temperature element by a Tufnol collar cemented to the tip with Araldite.

Radiation protection. It is normal practice to protect a thermometer from radiation by surrounding it with a radiation shield. The presence of a shield round a flat-plate thermometer, however, gives rise to an increment in air speed over the thermometer. In incompressible flow this increment is a constant proportion of the free air speed and therefore is of no importance in as far as variations in speed-correction coefficient are concerned, but at high Mach numbers this is no longer so as the interference effects are no longer linear with respect to air speed. At high Mach numbers also there is the additional disadvantage of interference from shock waves formed on the shield. Outrigging such as a shield is, besides, always unpopular with aircraft designers because of the drag it represents and the turbulence it introduces into the airstream ahead of the supporting aerofoil. Flat-plate thermometers, therefore, apart from special types such as the sonic-suction thermometer, due to Dunning (1947), must rely on other means of protection from radiation. Protection for the conical head thermometer was therefore provided by making the outer cover of the temperature element as highly reflecting as possible.

The outer cover made of a super-pure aluminium base alloy was anodized to give electrical insulation on the inside. The outside was polished mechanically and anodized and polished electrolytically to give a hard reflecting surface. Good results were obtained with BA SP 16 - WP aluminium alloy which contains small percentages of magnesium and silicon for hardness and ease of machining. When electrolytically polished, the absorptivity for visual wave lengths, according to the manufacturers, is in the region of .15. It is not known yet how long the good reflecting properties of the surface will survive exposure in flight and if it is found that reflectivity decreases considerably during use it may be necessary to renew the outer cover from time to time to maintain a good reflecting surface.

The thermometer will be exposed to solar radiation both direct and reflected and also to long-wave radiation from below; it will also lose heat by radiation from itself. The error in temperature from these effects will depend on the rate of heat exchange per degree of temperature difference between the thermometer and the air stream. Some calculations for various pressure heights and at two different air speeds have been made and are given in Table 5. The intensity of solar radiation at the top of the atmosphere was taken as .032 cal. cm.$^{-2}$sec.$^{-1}$ and allowance for diminution due to passage through the atmosphere has been made by use of a diagram provided by Väisälä (1948). In calculating the effect of the reflected solar radiation the albedo of the earth's surface has been taken as .35 following Scrase (1953), and two solar altitudes have been considered, namely 60 and 30 degrees. The emissivity of the earth's surface for long-wave radiation has been taken as .95 after Houghton and Brewer (1955). Absorptivity of the reflecting outer cover of the thermometer for visual radiation was taken as .15 but, for comparison, calculations have also been made for an absorptivity of .33 which might represent the state of the reflecting surface after some time in use. The emissivity for long-wave radiation (10μ)

/was

was also taken from Scrase (1953) as .03, as no figures were available from the manufacturers.

The following formulae and assumptions were used:-

(i) Direct solar radiation

$$Q_1 = \varepsilon_1 \; I_p \, S_1$$

(ii) Reflected solar radiation

$$Q_2 = K \, \varepsilon_1 \, R \, I_s \sin h. \, S_1$$

Allowance was made for loss in reflected radiation by re-transmission from ground level to the thermometer.

(iii) Long-wave radiation exchange with earth

$$Q_3 = B \, \varepsilon_2 \, (\varepsilon_3 \, T_3^4 - T_1^4) \, \frac{S_2}{2}$$

(iv) Long-wave radiation upwards: (downwards radiation from above assumed negligible)

$$Q_4 = B \, \varepsilon_2 \, (- T_1^4) \, \frac{S_2}{2}$$

(v) Rate of heat exchange with air stream: (considering the thermometer as a flat-plate, see Goldstein (1943))

$$Q_5 = \frac{.686 \sigma^{\frac{1}{3}} k \, S_2}{l} \left(\frac{U_1 \, l \rho}{\mu} \right)^{\frac{1}{2}} . \Delta T$$

Meaning of symbols used:-

ε_1 : emissivity of thermometer surface considered as grey body.

ε_2 : ditto for long-wave radiation (10μ), assumed to be .03 after Scrase (1953).

ε_3 : emissivity of earth's surface for long-wave radiation, assumed .95 after Houghton and Brewer (1955).

I_p: intensity of solar radiation at pressure level p in atmosphere.

I_o: ditto at top of atmosphere (.032 cal./cm.^{2}).

I_s: ditto at ground level.

S_1: projected area of temperature sensitive surface of thermometer (.45 cm.^{2}).

S_2: total exposed area of temperature sensitive area of thermometer (.46 cm.^{2}).

σ : Prandtl number (values taken from Clark, 1951).

/B:

B: Stefan-Boltzmann coefficient, 1.37×10^{-12} cal. cm.$^{-2}$ sec.$^{-1}$ deg. C.$^{-4}$.

T_1: Temperature in degrees absolute of thermometer surface.

T_3: ditto of earth's surface.

k: coefficient of thermal conductivity, after Taylor and Johnston (1946).

U_1: air speed in cm. sec.$^{-1}$ at the surface of the thermometer deduced from Fig.7 as .95 of free stream air speed.

l: length of exposed surface of temperature sensitive surface of thermometer in direction of air stream, 0.7 cm.

μ: coefficient of viscosity of air at thermometer surface, after Johnston and McCloskey (1940).

ρ: density of air at thermometer surface.

K: shape and orientation factor of thermometer. For horizontal surface K = 1, for sphere K = 2; as a compromise K was taken as 1.5.

R: albedo of the earth's surface, .35.

h: solar altitude.

/Table 5.

Table 5. Heat economy and radiation errors of a conical-head thermometer

Rate of heat exchange	Solar altitude	PRESSURE LEVEL (mb.)															
		100				300				500				900			
		U (m.p.h.)				U (m.p.h.)				U (m.p.h.)				U (m.p.h.)			
		200		500		200		500		200		500		200		500	
		ε_1		ε_1		ε_1		ε_1		ε_1		ε_1		ε_1		ε_1	
(cal. x 10^{-3})	h	.15	.33	.15	.33	.15	.33	.15	.33	.15	.33	.15	.33	.15	.33	.15	.33
Q_1	60	2.14	4.70	2.14	4.70	2.07	4.56	2.07	4.56	1.96	4.32	1.96	4.32	1.75	3.85	1.75	3.85
	30	2.10	4.61	2.10	4.61	2.01	4.42	2.01	4.42	1.86	4.08	1.86	4.08	1.62	3.57	1.62	3.57
Q_2	60	2.02	4.45	2.02	4.45	2.07	4.56	2.07	4.56	2.17	4.78	2.17	4.78	2.44	5.37	2.44	5.37
	30	1.02	2.25	1.02	2.25	1.05	2.30	1.05	2.30	1.10	2.41	1.10	2.41	1.23	2.71	1.23	2.71
Q_3		.13		.10		.11		.07		.07		.02		-.06		0	
Q_4		-.07		-.10		-.09		-.13		-.13		-.18		-.20		-.25	
$Q_5/\Delta T$		5.17		8.18		8.95		14.15		11.46		18.12		15.22		24.07	
$Q_1+Q_2+Q_3+Q_4$	60	4.22	9.21	4.16	9.15	4.16	9.14	4.08	9.06	4.07	9.04	3.97	8.94	4.05	8.96	3.94	8.97
	30	3.18	6.92	3.12	6.86	3.08	6.74	3.00	6.66	2.90	6.43	2.80	6.33	2.71	6.02	2.60	6.03
ΔT °C	60	.82	1.78	.51	1.12	.46	1.02	.29	.64	.36	.79	.22	.49	.27	.59	.16	.37
	30	.62	1.34	.38	.84	.34	.75	.21	.47	.25	.56	.15	.35	.18	.40	.11	.25

/Pressure

Pressure levels of 100, 300, 500 and 900 mb. and air speeds of 200 and 500 m.p.h. have been considered.

The following values of air temperature were chosen corresponding to the different pressure levels:-

Pressure level (mb.)	100	300	500	900
Air temperature (°A)	216	229	252	281

For speeds of 500 m.p.h., 24 degrees were added to give the surface temperature of the thermometer, and at 200 m.p.h., 4 degrees were added.

From Table 5 it is seen that the greatest errors occur at high altitudes where the rate of heat exchange with the air stream is least. To ensure that errors are kept to $\frac{1}{2}$ degree or less a good reflecting surface must be maintained and the fastest speeds used.

Mounting for thermometer. Whereas a total-head thermometer may be mounted on any forward facing site clear of engine exhaust or induced turbulence, a flat-plate thermometer must be mounted in an air stream undisturbed by the aerodynamics of the aeroplane. To obtain absolute independence of aerodynamic influence would require an elaborate platform not justified for routine measurement work. The conical-head thermometer therefore has been mounted on a sting which will carry it some 2 ft. in front of the point of fixture to the aircraft. It is intended where permissible to mount the thermometer and sting protruding from the leading edge of a narrow section aerofoil such as a wing or tail. The shortness of the sting makes it inadvisable to place it on the forward end of a large shape such as the fuselage.

Supersonic speeds. Although the conical-head thermometer was designed with subsonic speeds in mind, the conical shape is suitable for use in supersonic flow. Taylor and Maccoll (1933) showed that for a 20° angle cone in axial supersonic flow, for Mach numbers greater than 1.035, the shock wave is attached at the nose of the cone and the pressure field is uniform over the surface of the cone. It follows of course that the velocity field is also uniform over the conical surface. Now the relationship which exists in subsonic flow between the temperature rise on a flat-plate and the square of the local surface air speed has been shown by Eber (1952) to hold also in supersonic flow up to Mach number 5 at least.

This means that the formula for the recovery factor in laminar flow namely

$$\lambda = 1 - \left(\frac{U_1}{U_0}\right)^2 (1 - \sigma^{\frac{1}{2}}) \quad \text{(see Clark, 1951)}$$

holds at least up to M 5.

Tables for the flow speed along conical surfaces at supersonic speeds have been published by Kopal (1947) of the Massachusetts Institute of Technology. Using the values of U_1 obtained from these tables for a 20° angle cone and using the value for $\sigma^{\frac{1}{2}}$ from Clark (1951) for 500 mb., namely .846, λ has been calculated for various Mach numbers: the results are given in Table 4.

Table 4. Recovery factor at supersonic speeds for a 20° angle conical thermometer in axial flow

U_1/U_c	.4	.45	.50	.55	.60	.65	.70	.75	.80	.85	.90
M	1.0902	1.2330	1.4028	1.5957	1.8165	2.0750	2.3869	2.7794	3.3041	4.0748	5.4223
λ	.8730	.8675	.8649	.8631	.8616	.8604	.8591	.8580	.8569	.8556	.8543

/U_c

U_c is the velocity of the air if allowed to expand into a vacuum.

$U_c = U_o^2 \cdot \left\{ 1 + \frac{2}{\gamma - 1} \frac{1}{M^2} \right\}$, subscript $_o$ indicates free stream values.

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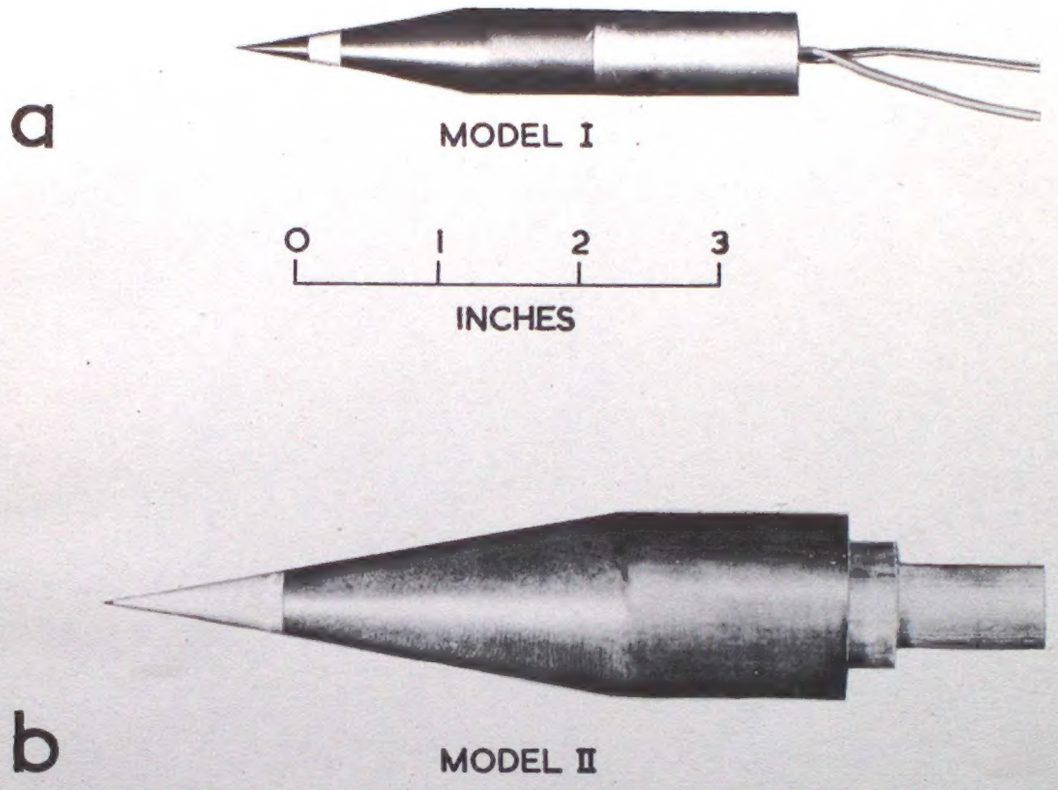


Fig.1. Wind tunnel models

(a) Conical thermometer Model I

(b) Conical thermometer Model II

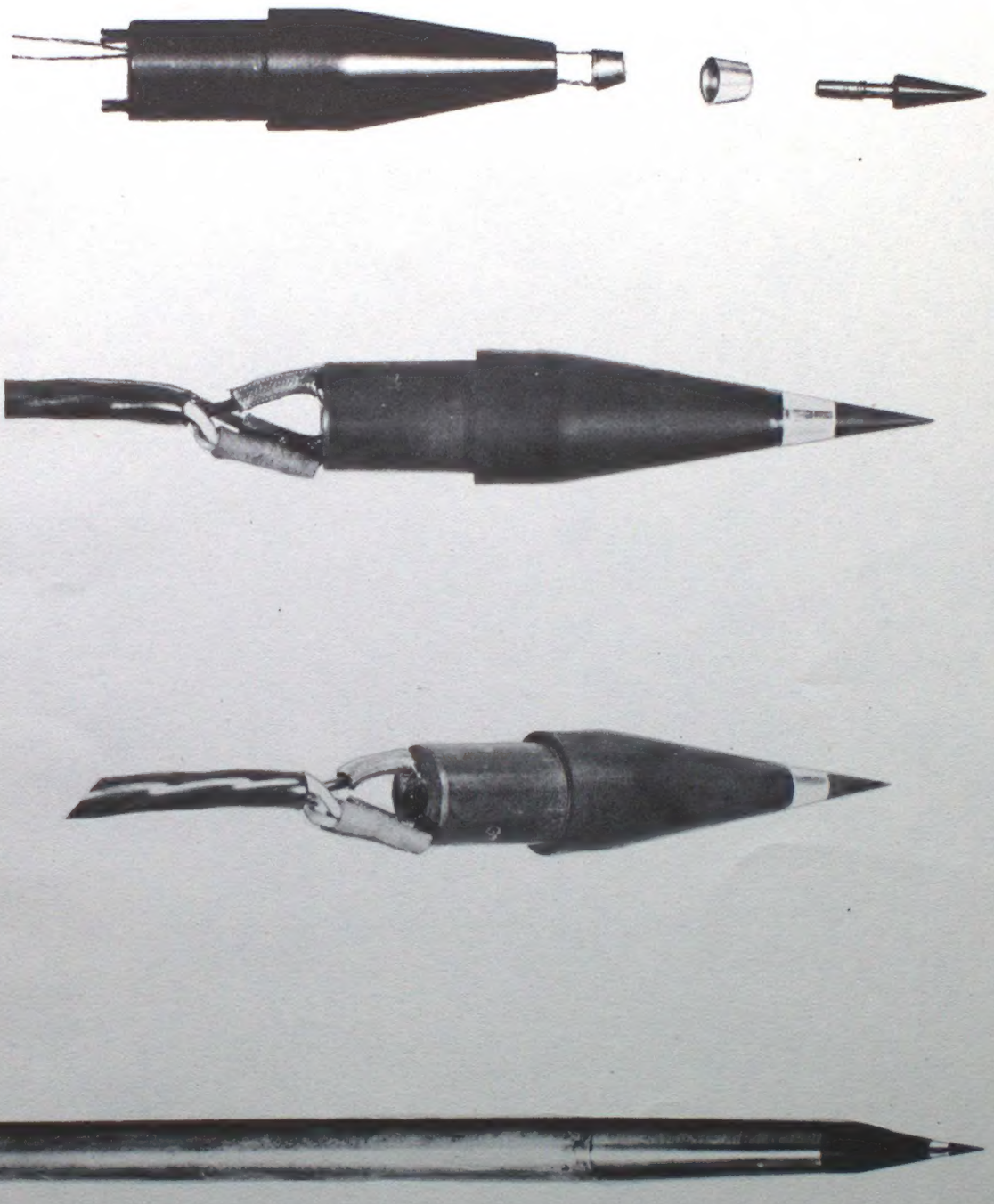


Fig.2. Conical head thermometer - prototype

(a) Exploded view showing parts before assembly

(b) and (c) Assembled thermometer. The two free leads shown are compensating leads

(d) Thermometer mounted on a sting

FIG. 3 Model I : λ against Mach No.

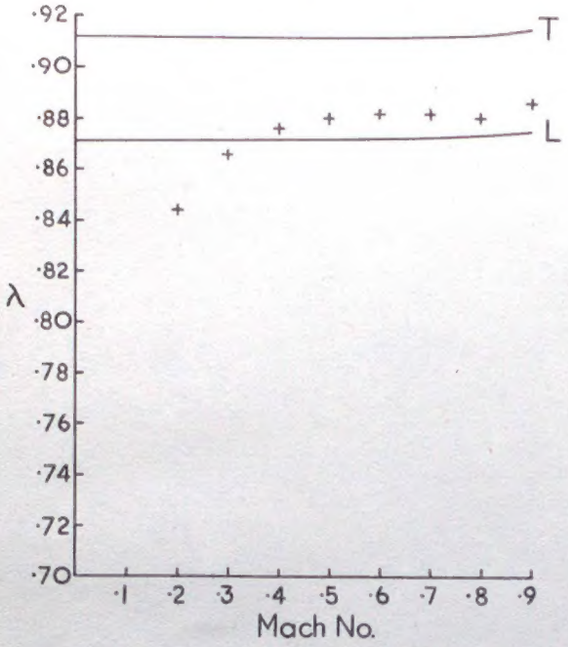
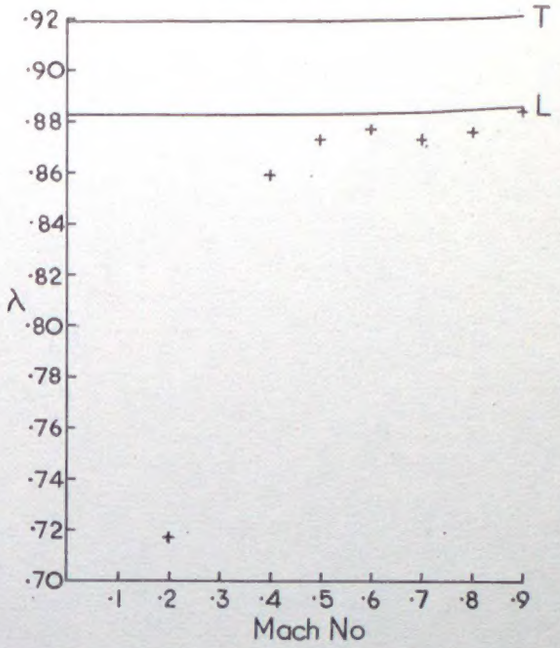


FIG. 4 Model II : λ against Mach No.



T : Calculated for turbulent boundary layer assuming no heat conduction along the surface
L : Ditto for laminar boundary layer

FIG. 5 Model I : λ against Reynolds No.

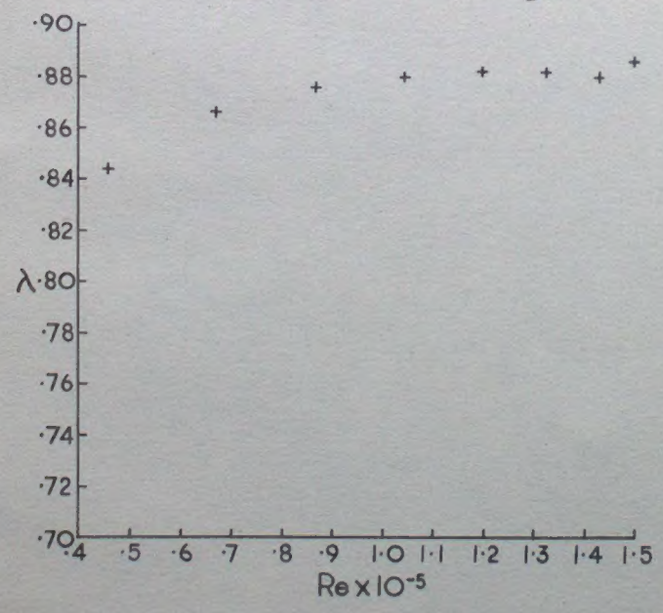


FIG. 6 Model II : λ against Reynolds No.

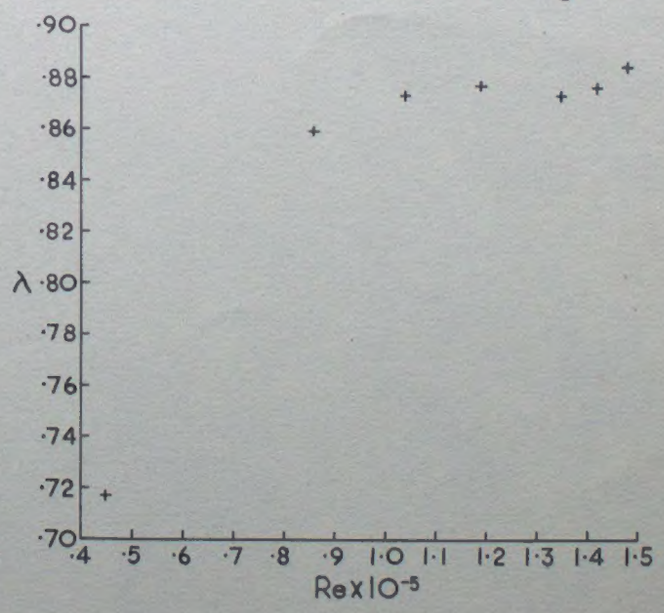
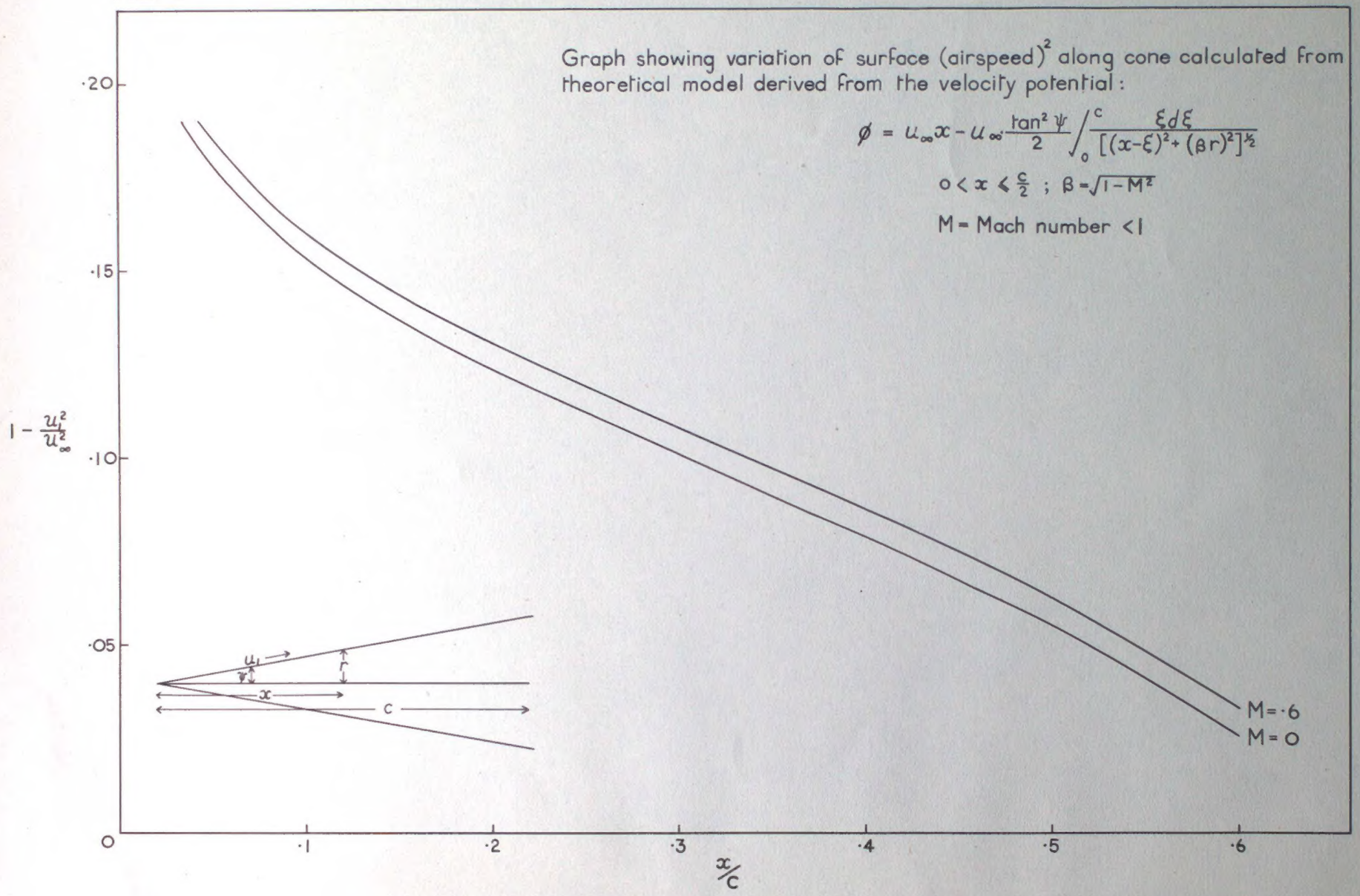


FIG. 7


Graph showing variation of surface (airspeed)² along cone calculated from theoretical model derived from the velocity potential:
$\phi = u_\infty x - u_\infty \frac{\tan^2\psi}{2} \int_0^c \frac{\xi\, d\xi}{[(x-\xi)^2 + (\beta r)^2]^{1/2}}$
$0 < x \leq \frac{c}{2}$; $\beta = \sqrt{1-M^2}$
M = Mach number <1
$1 - \frac{u_l^2}{u_\infty^2}$
·20
·15
·10
·05
0
·1
·2
·3
·4
·5
·6
$\frac{x}{c}$
M=·6
M=0
u_l
r
x
c